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P. 16

INTRODUCTION

The existence of stellar mass loss in the red giant phase was first conclusively demonstrated almost thirty years ago by Deutsch (1956, 1960), and, since then, there have been many quantitative estimates of mass loss rates, \dot{M} , for such stars published in the literature. In this review, I shall not present an exhaustive discussion of all such previous studies, but, rather selectively discuss those areas with which I am most familiar. This paper will consider all stars that are cooler than the blue edge of the Cepheid instability strip and evolved significantly ($\sim 2^m$) from the zero-age main sequence (ZAMS) to be cool giants and supergiants (see Fig. 1). Pre-main sequence stars, and giants in binaries that are "close" enough for the mass loss process to be affected significantly by the presence of the companion, will be excluded from further consideration.

In addition to the "direct" techniques for measuring \dot{M} , there are "indirect" techniques that have been used sometimes: typically, these involve an "inferred" present mass being known (say from the position of a star in the H-R diagram and comparison with stellar evolution tracks) combined with a hypothesis concerning the "initial" or "final" mass state of the star, and the timescale for evolution between "then" and "now." Though such indirect methods for estimating \dot{M} can be very useful, they will not be discussed further in this review. Two obvious limitations in their use are (a) that they are highly dependent on the accuracy of the particular evolutionary tracks adopted, and (b) they provide information on the integrated mass loss, Δm , between two times, viz.:

$$\Delta m = \int_{t_1}^{t_2} \dot{M}(t) dt \quad (1)$$

and not on the instantaneous mass loss rate \dot{M} at any particular time; thus, one cannot discriminate between continuous and discrete mass loss episodes.

There have been many previous reviews on mass loss and stellar winds in cool giants and supergiants: Reimers (1975, 1977, 1981, 1984) and his collaborators have been perhaps the major source of accurate mass loss values and important reviews. Other important reviews have been presented by Dupree (1981, 1983), Goldberg (1979), Zuckerman (1980), and Linsky (1981). Finally, a conference at UCLA in June 1984 was devoted to "Mass Loss from Red Giants"; the proceedings contains important review papers on ultraviolet spectroscopic diagnostics (Linsky 1985), far-infrared and sub-

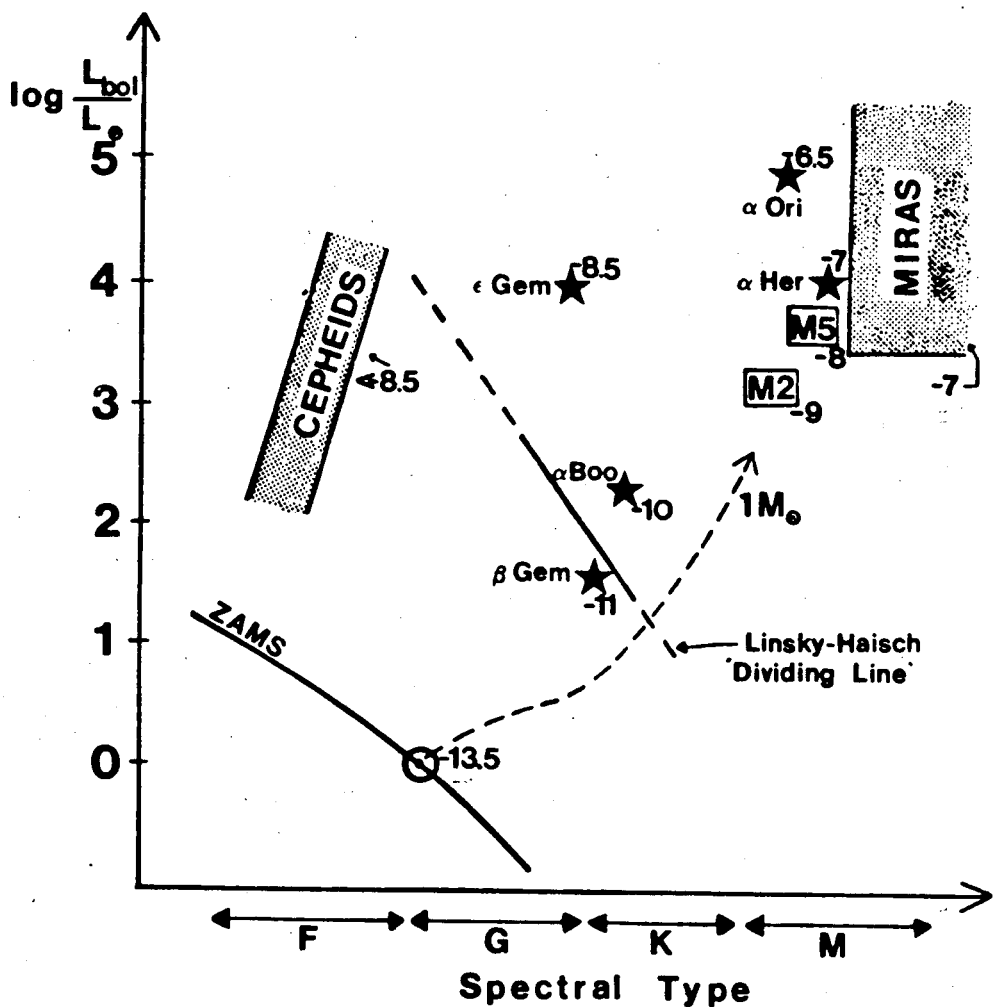


Fig. 1. A schematic H-R diagram showing the locations of several individual stars and groups of stars with their mass loss rates in terms of powers of $10 M_{\odot}/\text{yr}$.

millimeter photometric techniques (Werner 1985), infrared spectroscopic techniques (Wannier 1985), 21-cm line and radio continuum diagnostics (Knapp 1985), OH, H₂O and SiO maser diagnostics (Bowers 1985), and proposed mass loss mechanisms (Holzer and MacGregor 1985). Most of the papers presented at the UCLA conference dealt with mass loss in the most evolved, luminous red giants of spectral types M and C.

In this review, I will avoid re-capitulating the details of the well-established techniques for determining \dot{M} in cool giants and instead concentrate on addressing questions such as: (i) How accurately can \dot{M} values be estimated for these stars? (ii) What are the trends of the "bulk" properties of stellar winds — parameters such as \dot{M} , wind velocity v_w and wind temperature T_w — with stellar properties such as luminosity, effective temperature, mass, etc.? (iii) What do we know about mass loss in Cepheids? In G and K giants and supergiants? (iv) Can the present data on mass loss rates in cool giants be represented by simple "scaling" laws such as have been proposed by Reimers (1975) and Goldberg (1979)?

For convenience, I have divided the cool, luminous portion of the H-R diagram into eight sub-regions, namely: (i) Cepheid variables: e.g., δ Cep (F5 Ib-G2 Ib); (ii) G and K giants with coronae: e.g., β Gem (K0 IIIb) and β Cet (K0 III); (iii) hybrid-atmosphere G and K bright giants: e.g., α TrA (K2 Ib-IIIa); (iv) G and K supergiants, and K giants, with cool ($\sim 10^4$ K) winds, e.g., ϵ Gem (G8 Ib), α Boo (K1 IIIb), and α Tau (K5 III); (v) early to middle M giants with cool winds: e.g., α Cet (M1.5 IIIa) and β Peg (M2.5 II-III); (vi) early to middle M supergiants, with cool winds: e.g., α Ori (M1-2 Ia-Iab) and α^1 Her (M5 Ib-II); (vii) late M giants such as Mira variables: e.g., o Cet (M7 IIIe); and (viii) very evolved objects with dense molecular outflows: e.g., IRC + 10216 (C6).

BASIC METHODS FOR DETERMINING MASS LOSS RATES

The best-known technique for finding \dot{M} in cool giants is the use of circumstellar line features superimposed on the stellar spectrum by the expanding gas in the wind. Depending on the specifics of the particular line (how it is excited and where it is predominantly formed), the wind will produce either a P Cygni-type feature (blue-shifted absorption accompanied by an emission peak, somewhat red-shifted relative to the stellar radial velocity) or a simple, blue-shifted absorption line. The wind velocity v_w can be directly obtained from the observed blue shift; the column density of atoms of the specified element Z in that particular ionization (i) and excitation (e) state, $N_c(Z_{i,e})$, can be determined using some form of radiative transfer calculation ranging from approximations such as curve-of-growth and Sobolev escape probability methods to "exact" solutions in the observer's or co-moving frame. The column density of hydrogen $N_c(H)$ can be deduced from:

$$N_c(H) = N_c(Z_{i,e}) \frac{N_c(Z_i)}{N_c(Z_{i,e})} \frac{N_c(Z)}{N_c(Z_i)} \frac{N_c(H)}{N_c(Z)} \quad (2)$$

and, finally, using the equation of continuity, together with an assumed geometry and radial dependence, the total mass loss rate \dot{M} can be found. For example, in a spherically symmetrical wind which is expanding with constant velocity v_w then

$$\dot{M} \approx 3 \times 10^{-15} M_{\odot} \text{ yr}^{-1} \left(\frac{R_1}{R_{\odot}} \right)^{-1} \left(\frac{N_c(H)}{10^{18} \text{ atoms cm}^{-2}} \right)^{-2} \left(\frac{v_w}{\text{km s}^{-1}} \right), \quad (3)$$

where R_1 is the inner edge of the region in the wind containing significant material in the given ionization and excitation state.

Most of the inaccuracy in deriving \dot{M} using this type of technique applied to cool giants (e.g., Sanner 1976; Bernat 1977; Hagen 1978) lies not in the details of the radiative transfer but in the other model-dependent parameters such as the excitation correction $N_c(Z_1)/N_c(Z_1;e)$ (needed for a non-resonance line), or the ionization correction $N_c(Z)/N_c(Z_1)$, or the location of the inner edge R_1 . Another source of error that is present in any determination of \dot{M} , either explicitly or implicitly, is the uncertainty in the distance D of the star in question. Typically, the mass loss rate is proportional to the distance to a power between one and two, and thus the resultant proportional error in \dot{M} , $\delta\dot{M}/\dot{M} \sim (1-2)(\delta D/D)$. I estimate that the typical $\delta D/D$ for a cool supergiant or giant is \pm a factor of 2; for example, the well-studied M supergiant α Orionis has been variously estimated to be at 96 pc (White 1980), 205 pc (Wilson 1976), or 400 pc (Knapp and Morris 1985). A final complication in the circumstellar line technique is the identification of the circumstellar effects present in a line which may in addition have an underlying photospheric absorption component and an overlying interstellar absorption component. As an illustration of the order of magnitude uncertainty possibly introduced by these effects, Bernat (1982), in his study of ultraviolet circumstellar absorption lines in the wind of α^1 Scorpii, obtained total column densities from different lines ranging over almost two orders of magnitude. Reimers (1985) believes that the major reason for this discrepancy is the presence of substantial interstellar absorption in some of the lines used by Bernat in his analysis.

One valuable technique that can be used to accurately identify R_1 makes use of the fact that some cool, luminous stars have hotter secondary companions that orbit within their stellar wind regions and thus show circumstellar absorption features in their spectra. Assuming that the physical separation ΔR of the two stars in the binary is known, then clearly $R_1 = \Delta R$ in this case. This technique has been used to estimate \dot{M} for the M primaries in the visual binaries α Her (M5 Ib-II + (G5 III + F2 V)) (Deutsch 1956; Wilson 1960; Reimers 1977b, 1978), α Sco (M1.5 Ia-b-Ib + B4 Ve) (Kudritzki and Reimers 1978; van der Hucht, Bernat and Kondo 1980; Bernat 1982) and α Cet (M7 IIIe + wd/) (Yamashita and Maehara 1978; Reimers and Cassatella 1985) and for the K and M supergiant primaries in the eclipsing binaries ζ Aur (K4 II + B8 V), 31 Cyg (K2 II + B3 V), 32 Cyg (K3 Ib + B3 V) (Che, Hempe and Reimers 1983) and δ Sge (M2 II + A0 V) (Reimers and Schröder 1983). Although this method does much to

reduce one source of uncertainty, there are additional new factors that must be considered? Does the presence of a companion within a cool giant's wind affect the structure of the wind significantly? Clearly, a hot companion will directly alter the ionization balance in at least the continuous portion of the cool wind in which it is immersed, and this effect must be included in any analysis. In addition, one could imagine that the gravitational perturbation of the secondary might alter the mass flux and velocity of the surrounding stellar wind in some ways also. Thus, while binarity may be a useful tool in explaining cool giant winds, all of its ramifications must be carefully explored.

Over the last decade and a half, a whole new range of methods, in addition to the "classic" circumstellar line techniques, have been applied to estimate mass loss in cool stars, that I shall refer to as "volumetric" techniques because they yield volume emission measure-type quantities rather than column densities. In order of decreasing ionization level, these methods include:

(i) Thermal X-ray emission from coronal-type winds with $T_w \sim 10^6 - 10^{7.5}$ K. In most cool stars, most of the X-ray emission probably originates from closed, magnetic structures above active regions rather than open, "coronal-hole"-type outflowing regions. Nevertheless, the observed X-ray luminosity L_x can provide an upper limit to the wind emission measure. To translate this into an upper limit to the coronal mass loss rate \dot{M}_{cor} , one must know a representative outflow velocity v_w . By solar analogy, we assume that v_w is close to escape velocity in coronal wind stars, and that the expanding corona is homogeneous and spherical, then

$$\dot{M}_{cor} \approx R_*^{1/2} L_x^{1/2} v_w \quad (4)$$

(ii) Free-free continuum emission at microwave (and perhaps far-infrared) wavelengths from the ionized components of stellar winds, (i.e., $T_w \gtrsim 10^4$ K); e.g., Perger, Giuliani and Knapp (1983) and Drake and Linsky (1985), as applied to cool giants. In the optically thick regime at frequency ν

$$\dot{M}_{ion} \approx L_{rad}^{0.75} v_w^{-0.45} T_w^{-0.075} \quad (5)$$

where L_{rad} is the monochromatic radio luminosity. Once again, constant velocity outflow and spherical geometry have been assumed; notice the very weak dependence of temperature in this relation.

(iii) 21-centimeter emission from atomic hydrogen present in the cool components of stellar winds (i.e., $2 \times 10^3 \lesssim T_w \lesssim 8 \times 10^3$ K); e.g. Zuckerman, Terzian and Silverglate (1980) and Knapp and Bowers (1983), as applied to cool giants (with negative results, in all cases, to date). Making the usual simplifying assumptions, it can be shown that

$$\dot{M}_{HI} \approx L_{HI} v_w^2 R_{max}^{-1} \quad (6)$$

where L_{HI} is the 21 cm luminosity, R_{max} is the outer edge of the HI region, and we have assumed that the region is optically thin.

(iv) Emission lines from molecules such as CO and OH present in the molecular components of stellar winds ($T_w \lesssim 2-3 \times 10^3$ K); e.g. the CO J = 1-0 line at 2.6 mm (Knapp and Morris 1985) and CO J = 2-1 line at 1.3 mm (Knapp *et al.* 1982). The mass loss of CO molecules is of the form

$$\dot{M}_{\text{CO}} = L_{\text{CO}} v_w^2 \quad (7)$$

in the optically thick case, where L_{CO} is the luminosity in the CO line. In order to estimate the total molecular mass loss rate ($\sim \dot{M}_{\text{H}_2}$), it is also necessary to know the ratio $f = n(\text{CO})/n(\text{H}_2)$. The value of this ratio in late M and C stars is not necessarily easy to estimate; typical values found in the literature range from 8×10^{-5} (Knapp, Phillips and Huggins 1980) to 8×10^{-4} (Morris 1980). Thus, an additional uncertainty of $\sim \pm$ a factor of 3 in the final mass loss rate results from this.

(v) "Excess" infrared emission at 10 μm or in the far-infrared from the dust component of stellar winds ($T_w \lesssim 2 \times 10^3$ K); e.g., Gehrz and Woolf (1971) and Knapp (1985b). The loss rate of grains is of the form $\dot{M}_{\text{gr}} = L_{\text{IR}} v_w$, where L_{IR} is the luminosity attributed to the dust; making additional assumptions about the size and density of the grains, one can then estimate \dot{M}_{gr} . Gehrz and Woolf further assumed a solid-to-gas mass ratio s/g of 1/250 and hence obtained total mass loss rates for their sample of stars. Knapp empirically calculated s/g by comparing dust mass loss rates and CO mass loss rates for a large sample of stars; she found $s/g = 1/160$ for oxygen-rich stars and $s/g = 1/390$ for carbon-rich stars, with remarkably small scatter over 4.5 orders of magnitude range in the total mass loss rates.

MASS LOSS IN CEPHEID VARIABLES

Cepheid variables are typically F giants and supergiants of 3 to 15 M_\odot that pulsate with periods from ~ 1 to ~ 50 days. Discrepancies between evolutionary and pulsationally derived masses have been referred to as the "Cepheid mass anomaly" (e.g., Christy 1968, Cox 1980), and have led some researchers to propose that the differences can be resolved if significant mass loss occurs before and/or during the Cepheid phase. The extent and reality of the Cepheid mass anomaly is still apparently a matter of active debate [e.g., Burki (1984) concluded that it exists only for single Cepheids with periods $\geq 10^d$, while Willson and Bowen (1984) stated that it is most serious for the shorter period Cepheids], and thus the amount of mass loss implied is also unclear; ranging from $10^{-10} M_\odot \text{ yr}^{-1}$ (Cox, Michand and Hodson 1978) to $10^{-6} M_\odot \text{ yr}^{-1}$ (Willson and Bowen 1984). What is clear, however, is that, in the case of Cepheids, theoretical considerations have been the driving force behind the belief that there must be significant mass loss, rather than the available observational evidence which is, to say the least, not overwhelming. There is, in fact,

little direct evidence for substantial ($\dot{M} \gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$) mass loss in the general Cepheid population.

In what form would mass loss from a Cepheid variable take? It is now known that (a) Cepheids are not active, coronal-type stars since they are weak or undetectable in soft X-rays (Bohm-Vitense and Parsons 1983), and show only transient evidence for material at chromospheric ($T \sim 10^4$ K) and transition-region ($T \sim 10^5$ K) temperatures (Schmidt and Parsons 1982, 1984a); (b) they do not show permanent well-developed P Cygni profiles or blue-shifted absorption features, indicative of steady mass loss, in resonance lines such as Ca II H and K or Mg II h and k (e.g., Schmidt and Parsons 1984b); (c) they do not, in general, exhibit significant infrared excesses above the extrapolated photospheric continuum, although there are some exceptions such as RS Pup (see Gehrz and Woolf 1970); and (d) they are not radio continuum sources, at least at detection levels of 5-10 mJy, implying $\dot{M}_{\text{ion}} \lesssim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for Cepheids at distances of ~ 300 pc, with assumed wind velocities of $\sim 100 \text{ km s}^{-1}$.

Using the lack of permanent circumstellar absorption features in the Mg II lines, one can infer an upper limit to the wind column density in typical Cepheids that yields an upper limit to the mass loss rate \dot{M} with the functional form:

$$\dot{M} \lesssim 10^{-13} M_{\odot} \text{ yr}^{-1} (R_*/R_{\odot}) (v_w/\text{km s}^{-1}) \quad (8)$$

Thus, for a 10^d Cepheid we might expect $R_* \sim 100 R_{\odot}$ and $v_w \sim 100 \text{ km s}^{-1}$ to obtain an upper limit to \dot{M} of $\sim 10^{-9} M_{\odot} \text{ yr}^{-1}$. Thus, I conclude that all the presently available data on Cepheids are consistent with the typical steady mass loss rates lying in the range 0 to 10^{-9} - $10^{-8} M_{\odot} \text{ yr}^{-1}$. The only remaining way that significant mass loss ($\delta M \sim 5\text{-}50\% \times M_*$) can occur during the Cepheid phase (lasting $\sim 10^5$ - $10^{6.5}$ years according to evolutionary calculations), is in discrete, "shell-ejection" episodes of much shorter duration than the evolutionary timescales.

MASS LOSS IN CORONAL G AND K GIANTS

The only way to estimate \dot{M} for coronal giants is through either their X-ray or radio continuum emission. The former technique is probably most appropriate for the "inactive" X-ray giants like β Gem (KO III), which have $L_x \sim 10^{28} \text{ ergs s}^{-1}$. Assuming $v_w = 200 \text{ km s}^{-1}$ for such a coronal wind in a giant, one estimates $\dot{M}_{\text{cor}} \lesssim 2 \times 10^{-11} M_{\odot} \text{ yr}^{-1}$, where the inequality recognizes that closed magnetic loops may contribute significantly to the observed X-ray flux, even in relatively "quiet" stars. The "active" KO III star β Cet has $L_x \sim 10^{30} \text{ ergs s}^{-1}$, two orders of magnitude larger than β Gem, and implying in this case (since $\dot{M}_{\text{cor}} = L_x^{1/2}$), that $\dot{M}_{\text{cor}} \lesssim 2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$. The actual mass loss rate is probably much smaller than this upper limit for β Cet, since most of the X-ray emission is almost certainly from closed loops. The alternate way of estimating \dot{M} for coronal giants from their radio continuum emission has been employed by Drake and Linsky (1985). They detected no single, coronal

giants at 6 cm detection thresholds of ~ 0.2 mJy (3σ). Since we expect the radio emission from coronae to be optically thin, we cannot use the optically thick approximation given previously; it can be shown that, in the optically thin case:

$$\dot{M}_{\text{ion}} = 1.6^{0.5} v_w^{0.05} T^{0.175} R_*^{0.5} \quad (9)$$

For δ Gem and δ Cet, Drake and Linsky (1985) obtained upper limits to \dot{M}_{ion} of 4×10^{-10} and $7 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$, respectively.

It thus seems clear that coronal giants are not losing significant mass in this phase ($\dot{M}_{\text{cor}} \lesssim 2 \times 10^{-11} - 2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$). If $R = 10 R_{\odot}$ for a K0 III star and the mass flux per unit area is the same as the sun, its mass loss rate would be $2.5 \times 10^{-12} M_{\odot} \text{ yr}^{-1}$, consistent with the upper limits to the mass flux derived from the X-ray data.

MASS LOSS IN HYBRID-ATMOSPHERE STARS

This somewhat controversial class of luminous G and K stars was first identified by Hartmann, Dupree and Raymond (1980) by the simultaneous presence in their spectra of high-velocity absorption components ($v_w \sim 70\text{--}150 \text{ km s}^{-1}$) in the Mg II and/or Ca II resonance lines indicating a cool wind ($T_w \sim 10^4 \text{ K}$), and emission lines of species such as C IV indicative of substantial material at temperatures $\sim 10^5 \text{ K}$ (typical of a "transition region" between chromosphere and corona in coronal stars). Drake and Linsky (1985) derived upper limits to \dot{M}_{ion} for these stars of $\sim 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$ based on their non-detections at 6 cm. The well-developed P Cygni profiles exhibited by the Mg II resonance lines in hybrid stars make them good candidates for line profile modeling to determine independently their mass loss rates. Because these lines are resonance lines, it is possible that partial redistribution effects may be significant, but the relatively high velocity of these winds suggest that a simple Sobolev escape probability approach should yield reasonably dependable results.

MASS LOSS IN G AND K GIANTS AND SUPERGIANTS WITH COOL WINDS

These stars have blue-displaced absorption components typically in the Mg II and (sometimes) Ca II resonance lines, indicating outflows of $10\text{--}50 \text{ km s}^{-1}$ in giants and $10\text{--}100 \text{ km s}^{-1}$ in the supergiants. The most reliable methods to estimate \dot{M} for these stars are, in my opinion, line profile modeling, and radio continuum techniques, since a significant fraction (10–100%) of the wind is probably ionized. Che *et al.* (1983) derived mass loss rates of $\sim 1 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ for the K supergiants in three ζ Aurigae binaries. Mallik (1982) estimated \dot{M} for 23 late G and K supergiants in the range 10^{-7} to $10^{-5} M_{\odot} \text{ yr}^{-1}$ from modeling the H α absorption cores in their spectra. These latter values seem to be too high by 1 to 2 orders of magnitude, since the results of any two-level atom type analysis using non-resonance lines are uncertain and the modulation of the intrinsic stellar H α absorption profiles of these

stars by the wind is very subtle so that separating the two effects is difficult. Reimers (1975) quotes values of \dot{M} in the range 10^{-8} to $2 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for several G and K Ib supergiants determined by circumstellar line modeling.

Few specific estimates exist for mass loss in K giants. Wilson (1980) estimated an upper limit to \dot{M} for K2 III stars with no circumstellar absorption in their Ca II H and K lines of $\sim 10^{-10} (R_{\star}/20 R_{\odot}) M_{\odot} \text{ yr}^{-1}$. Reimers (1975) estimated $\dot{M} = 2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ for K0-2 III stars and $6 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ for K3-5 III stars. Drake (1984) estimated $2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ for the K1 IIIp star α Boo, based on a study of its Mg II k line using a spherically symmetric, co-moving frame radiative transfer solution. Drake and Linsky (1985) detected three cool wind K giants as 2 and/or 6 cm radio sources (α Boo, α Tau and β UMi) with inferred values of \dot{M}_{ion} of 7×10^{-11} , 8×10^{-11} , and $1 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ respectively. They did not detect any supergiants of the G and K type, implying upper limits to \dot{M}_{ion} of $\sim 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$.

The conclusions that I draw from the above are (i) \dot{M} values for K III's with cool winds are $2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ with a spread (either intrinsic or due to measurement uncertainties) of perhaps \pm a factor of 3. Given that typical evolutionary timescales for solar mass stars through this phase are 10^8 - 10^9 years, it seems most probable that most such stars do not lose significant mass ($\Delta m \sim 0.1 M_{\odot}$) before reaching the top of the red giant branch; and (ii) \dot{M} values for G and K (Ib) supergiants are less precise; detailed studies of the state of ionization expected in their winds would clarify the present situation. If they are completely ionized, then the radio results imply that $\dot{M} \lesssim 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, somewhat in contradiction with the Reimers' results that \dot{M} values for G and K Ib stars are mostly around $10^{-8} M_{\odot} \text{ yr}^{-1}$. This contradiction can be resolved if the ionization fraction of these winds is $\lesssim 20\%$, but this remains to be shown. For now, it seems plausible that $\dot{M} \sim 10^{-9}$ - $10^{-7} M_{\odot} \text{ yr}^{-1}$ for these stars, where the range is mostly due to measurement and ionization uncertainties.

MASS LOSS IN M0-M5 GIANTS AND SUPERGIANTS

The mass loss properties of these stars have been intensively studied, and it is impossible to itemize all the previous work. The reader is referred to the previous reviews listed in the introduction for more comprehensive details. The winds of these early M giants are typically of low velocity ($v_w \sim 10$ - 25 km s^{-1}), probably mostly neutral, and relatively cool ($T_w \sim 4$ - $8 \times 10^3 \text{ K}$). Circumstellar absorption features are seen in Mg II h and k, Ca II H and K, Mg I $\lambda 2852 \text{ \AA}$, and many lines in the optical region of the spectrum such as Al I $\lambda 3944 \text{ \AA}$, Cr I $\lambda 4254 \text{ \AA}$. These stars do not usually have significant near-infrared excesses (cf. Gehrz and Woolf 1971), but some of the supergiants (e.g., α Ori) do show CO emission lines in the millimeter range, suggesting that the outer regions of the winds ($\gg 10 R_{\star}$) may have cooled (to $\sim 2 \times 10^3 \text{ K}$) relative to the inner regions.

Despite the large body of work on mass loss in stars of this type, there is still no consensus on the exact values of \dot{M} for these stars; estimates for any given stars or generic types (such as M2 III stars) typically cover a range of 1.5 to 3 orders of magnitude. There is agreement, however, that with later spectral type and increasing stellar radius, the mass loss rates increase by about a factor of 10 between M2 and M5 for luminosity class III stars, with the "low" estimates being 2×10^{-10} (M2) and 3×10^{-9} (M5) $M_{\odot} \text{ yr}^{-1}$ and the "high" estimates being 1×10^{-8} (M2) and 1×10^{-7} (M5) $M_{\odot} \text{ yr}^{-1}$. It is my impression that there is a subjective bias toward overestimating \dot{M} values (bigger values produce more interesting consequences!). I therefore tend to favor the lower range of the estimates; they also are more compatible with an extrapolation of the previously mentioned K III \dot{M} estimates. I favor \dot{M} values which increase from $\sim 1 \times 10^{-9}$ to $\sim 6 \times 10^{-9}$ $M_{\odot} \text{ yr}^{-1}$ as the spectral type goes from M2 III to M5 III. If we assume that such stars are evolved from 2-5 M_{\odot} initial mass stars with corresponding evolutionary times from the ZAMS to the tip of the red giant branch of 10^6 to 10^7 years, the total mass loss during this phase once again appears to be small ($\Delta m < 0.1 M_{\odot}$).

The situation for early M supergiants and bright giants is even less well determined than for M giants, due to their greater distance uncertainties. \dot{M} estimates for the prototypical M2 supergiant α Ori [now suspected of being a binary or even triple system on the basis of recent speckle interferometric work (Karovska et al. 1986)] range from $\sim 10^{-7}$ to $\sim 10^{-5}$ $M_{\odot} \text{ yr}^{-1}$, and for the rather less luminous M5 Ib-II star α^1 Her they range from 10^{-8} to 10^{-6} $M_{\odot} \text{ yr}^{-1}$. Once again, taking the geometric mean of the extreme values in each case probably is not too far wrong, though I personally favor somewhat lower values of 3×10^{-7} and 6×10^{-8} $M_{\odot} \text{ yr}^{-1}$ for α Ori and α^1 Her, respectively. The former value for α Ori is in good agreement with the recent CO derived value given in Knapp and Morris (1985), if I correct their value of 1.4×10^{-6} $M_{\odot} \text{ yr}^{-1}$, assuming a distance of 400 pc, to 3.5×10^{-7} $M_{\odot} \text{ yr}^{-1}$, for the more commonly accepted distance of 200 pc (remember $\dot{M}_{\text{CO}} \propto D^2$). The latter value for α^1 Her is about a factor of two smaller than Reimer's (1977) value of 1.1×10^{-7} $M_{\odot} \text{ yr}^{-1}$. Two additional miscellaneous points about M supergiants are: (i) the \dot{M} determinations of Sanner (1976) [for α Ori, α^1 Her, and ten similar stars] are also in good agreement with the above two estimates; and (ii) the integrated mass loss during this phase is quite small ($\Delta m \ll 0.1 M_{\odot}$), since red supergiants are fairly massive stars ($M_{\star} \geq 10 M_{\odot}$) with short timescales in this phase ($\lesssim 10^5$ years).

MASS LOSS IN THE COOLEST M AND C STARS

The very latest evolved stars include Mira and semi-regular variables, and luminous carbon stars such as IRC + 10216. Mass loss from such stars was discussed in detail at the 1984 UCLA conference on "Mass Loss in Red Giants" and in a review by Zuckerman (1980), and this topic will not be extensively discussed here. The typical techniques determining \dot{M} in such stars involve molecular emission lines or

infrared excesses, since the winds (or at least the outer regions) appear to be very cool, as one might expect. [There does, however, appear to be a partially ionized region (a postshock cooling region or chromosphere), between the cool photosphere and similarly cool "outer" wind region that produces, in some cases, detectable Mg II and radio continuum emission: Wing and Carpenter (1978) detected Mg II emission in R Leo (M8 IIIe; Mira) and R Dor (M8 III; SRb), and at least three such stars have been detected at centimeter wavelengths.] The published mass loss rates for the Mira variables also range over about two orders of magnitude from $\sim 2 \times 10^{-8}$ to $2 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. A value of $\sim 1 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ for a typical Mira seems a reasonable compromise, and agrees well with the value recently determined for α Cen A itself from a study of the circumstellar wind lines seen in its usual companion α Cen B (Reimers and Cassatella 1985).

Finally, IRC + 10°216 (\equiv CW Leo) is often considered the prototype of a very evolved massive star. Its mass loss rate as determined from CO measurements has been variously estimated to lie between 4×10^{-5} and $1.5 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ (Kwan and Linke 1982; Knapp *et al.* 1982). Thus its wind is apparently one of the most extensive known among cool, evolved stars. In just 2.5×10^4 years, according to the above estimates, this star (of $\sim 12 M_{\odot}$?) will eject $1-4 M_{\odot}$, with significant effects on its subsequent evolution. The mass loss rate for this star is so much larger than for the other classes previously discussed that one is tempted to identify its present phase of mass loss with the short-lived "superwind" phase postulated on theoretical/empirical grounds by Renzini (1981). However, all of the presently available \dot{M} estimates for this star are based on CO measurements and should be confirmed by some independent means before being taken too literally.

DISCUSSION AND CONCLUSIONS

(a) Scaling laws

Over the last decade, there have been many attempts to obtain simple empirical "laws" relating mass loss for various types of both cool and hot stars as a function of the underlying stellar parameters, such as mass, radius, gravity, luminosity, etc. The scaling law most commonly used for cool evolved stars was first proposed by Reimers (1975), viz.:

$$\dot{M} = 4 \times 10^{-13} M_{\odot} \text{ yr}^{-1} \frac{L/L_{\odot}}{(g/g_{\odot})(R/R_{\odot})} \quad (10)$$

Reimers based the functional form of this "law" on physical arguments, and derived the constant of proportionality by a calibration using K and M supergiants and M giants for which he had "reliable" values of \dot{M} . Reimers did not propose that this relation could be used across the entire "cool" half of the H-R diagram to estimate \dot{M} values; he pointed out that it would overestimate the solar mass loss rate by a factor of 20, for example. Despite this caution, the "Reimers Scaling Law" has been

widely applied to many different types of cool stars. The standard practice has been to assume that the functional form is "correct" and to accommodate apparently contradicting results, say from comparison with evolutionary or pulsational considerations, by an extra multiplicative factor "c" which can be adjusted to bring about a better "fit." The value of c adopted or inferred has ranged from 0.25 (proposed by Wood and Cahn (1977) for Mira variables) up to 5 (proposed for OH/IR stars by de Jong 1983). Thus, c has itself "varied" by a factor of 20, casting doubt as to whether there is really an additional functional dependence omitted from the formula, or, whether the functional dependence on (L/gR) is correct.

Goldberg (1979) pointed out that the much simpler functional form $\dot{M} = 3 \times 10^{-12} M_{\odot} \text{ yr}^{-1} (R/R_{\odot})^2$ fits Reimers' (1977) data set as accurately as the Reimers' Scaling Law. In Table 1, I have assembled my adopted empirical \dot{M} values, and compared them with the \dot{M} values predicted by the Reimers' scaling law with $c = 0.75$. Inspection of this table shows that, if one accepts the empirical numbers as accurate, then: (i) the Reimers' scaling law overestimates \dot{M} 's for Cepheid variables, coronal G and K giants and "cool wind" K giants but underestimates \dot{M} for IRC + 10°216. (ii) It predicts \dot{M} values for hybrid stars at about the level of the 3 σ upper limits to \dot{M} obtained from radio data, suggesting that the predictions are at least a factor of two too high. (iii) For early M giants and supergiants, as one would expect, the law predicts values of \dot{M} within the "spread" of the empirical \dot{M} values, although closer to the "high" estimates, and above my "best guess" values by factors of 3 to 10. (iv) It predicts \dot{M} values for Miras that are close to the maximum in the range of empirical \dot{M} values.

The above suggests that a widespread application of the Reimers' (and, perhaps, any) scaling law to all cool luminous stars, including pulsators and non-pulsators, winds with temperatures ranging from 2×10^3 to 2×10^7 K, and velocities from 5 to 500 km s⁻¹, is, to say the least, debatable. However, it is interesting to note that a modified Goldberg relation of the form

$$\dot{M} = 2.5 \times 10^{-14} M_{\odot} \text{ yr}^{-1} (R/R_{\odot})^2 \left(\frac{v_{\text{esc}}}{v_{\text{esc}}^0} \right)^{\alpha}, \quad (11)$$

with an adopted $\alpha = 1$, does predict \dot{M} values in decent agreement with the empirical ones (see Table 1), for all the cool star classes considered here, except for IRC + 10°216 and similar objects. It also predicts the correct solar mass flux. An additional term has been added to reflect the intuition that, as the escape velocity from the stellar surface decreases, the mass flux from a stellar wind should increase. I do not attempt to justify the exact physical form of the term adopted here ($\propto v_{\text{esc}}^{-1} = (R/M)^{0.5}$) and, indeed, one might on simple physical grounds expect an inverse quadratic dependence on escape velocity. Lastly, it should be noticed that, for luminous M stars, the above formula typically predicts \dot{M} values 1/3 - 1/10 that estimated by the Reimers' scaling law.

Table 1

Mass Loss Rates in Cool Giants and Supergiants

Star or Class	Cepheid (10 ^d Period)	β Gem	α Boo	Early M Giant	Mid M Giant	α Ori	α^1 Her	α Cet	IRC + 10 ^o 216
Spectral Type	F I-III	K0 III	K1 IIIp	M2 III	M5 III	M1-2 Iab-Ia	M5 Ib-II	M6 IIIe	C 9,5
Luminosity L_{bol}/L_{\odot}	4,800	47	180	1,000	3,000	73,000	11,000	6,000	50,000
v_w (km s ⁻¹)	(150)	(180)	40	15	15	10	10	5	16
\dot{M}_{Drake}^a	$\leq 3 \times 10^{-8}$	$\leq 2 \times 10^{-11}$	2×10^{-10}	1×10^{-9}	6×10^{-9}	3×10^{-9}	6×10^{-8}	1×10^{-7}	8×10^{-5}
$\dot{M}_{\text{Reimers}}^b$	1.3×10^{-8}	9.4×10^{-11}	1.6×10^{-9}	9.0×10^{-9}	2.7×10^{-8}	1.4×10^{-6}	1.6×10^{-7}	4.4×10^{-7}	2.3×10^{-6}
$\dot{M}_{\text{modified}}^c$ Goldberg	3.1×10^{-10}	6.5×10^{-12}	1.0×10^{-10}	7.7×10^{-10}	3.1×10^{-9}	1.8×10^{-7}	3.4×10^{-8}	9.0×10^{-8}	1.0×10^{-6}
T_{ev} (years) ^d	6×10^5	$\geq 2 \times 10^8$	1×10^9	2×10^7	5×10^5	2.5×10^6	6×10^6	3×10^5	4×10^4
$\dot{M}^{\text{TeV}}_{\text{ev}}$ (M_{\odot})	$\leq 2 \times 10^{-3}$	$\geq 4 \times 10^{-3}$	0.2	0.02	3×10^{-3}	8×10^{-3}	4×10^{-3}	0.03	3.2

^aThese values are the "best" guess values that I have adopted in the text based on the present observational data, in $M_{\odot} \text{ yr}^{-1}$.

^bThese values are obtained using the Reimers' scaling law with $c = 0.75$.

^cThese values are obtained using the "modified" Goldberg scaling law.

^dPlausible evolutionary timescales for various types of stars.

(b) Final thoughts

For well-studied cool giants, I would estimate that the relative uncertainties in the empirical \dot{M} values are becoming tolerably small, say, $\delta\dot{M}/\dot{M} \sim \pm 0.5$ dex. Unfortunately, there are only a handful of such stars (most have been mentioned in this paper!) and these inhabit only a very limited range of parameter space in the H-R diagram. It is thus difficult to answer questions such as: (a) Do the mass loss properties of normal and pulsating stars differ significantly, or does the value of \dot{M} as a function of L_{bol} and T_{eff} vary smoothly throughout the entire cool, luminous portion of the H-R diagram? (b) Is there a significant increase in \dot{M} when a star becomes a Mira variable? (c) What stellar parameters influence \dot{M} ? (d) Can we assume that at a given location in the H-R diagram all stars have the same mass loss rate? This seems unlikely, since it is known that evolutionary effects can cause stars to transit back and forth through the red giant region, and thus, at a given combination of L_{bol} and T_{eff} one will find stars in very different evolutionary stages. Another factor which may influence \dot{M} is the chemical composition of the star: little is known, for example, about mass loss in Population II objects.

The data discussed in this review indicate that there are rough general trends of \dot{M} (and v_w , T_w) with location in the H-R diagram (see Fig. 1), but discontinuities or intrinsic spreads of up to an order of magnitude or more in \dot{M} are difficult to discern, due to the large uncertainties in our knowledge of mass loss in cool stars. I therefore believe that much additional research remains to be done, and suggest that the following be kept in mind: (i) Any method for finding the total \dot{M} of a stellar wind should be based on spectral lines or ionization stages that are not minor constituents of the circumstellar material; (ii) Mass loss rates cannot be estimated unless one has knowledge of the "average" physical conditions in the wind: at the very least, v_w and T_w , must be known. To obtain the highest precision (that is reached already for hot stars with winds), one must have information about the radial structure of the wind (e.g., the velocity law $v(r)$, and the temperature variation $T_g(r)$), and, possibly, azimuthal (or other non-spherical) structure, as well, particularly for binary stars. The work of Reimers, Stencel and collaborators on the stellar winds of the primary components of the eclipsing ϵ Aurigae and VV Cephei systems is indeed starting to yield such information (e.g., see the papers by Ahmad and Stencel, and Che-Bohnenstengel and Reimers in this workshop proceedings). However, the binary companion may change the structure of the primary's stellar wind, particularly in these relatively close binaries with P_{orb} less than say 5 to 10 years. For example, the abnormally high terminal wind velocities to be seen in evolved stars in such binary systems, if real, may be due to binarity. (iii) The highest accuracy values of \dot{M} for a particular star or class require completely independent techniques; e.g., millimeter emission lines of CO and optical circumstellar absorption features. When such independent methods yield consistent \dot{M} values then, assuming one has adopted accurate stellar parameters, there is a good

chance that the value of \dot{M} is accurate. (iv) Some stars like α Ori have had their mass loss measured by many different techniques, and can thus serve as "rosetta stones" to help us understand possible systematic errors in certain methods. Such "standards" should be chosen carefully, have accurately known stellar parameters, and have non-peculiar character. (It is not clear that α Ori is such a star due to the uncertainty in its distance and its possible multiple nature.)

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